RESEARCH REVIEW

Winter oilseed production for biofuel in the US Corn Belt: opportunities and limitations

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Abstract

Interest from the US commercial aviation industry and commitments established by the US Navy and Air Force to use renewable fuels has spurred interest in identifying and developing crops for renewable aviation fuel. Concern regarding greenhouse gas emissions associated with land-use change and shifting land grown for food to feedstock production for fuel has encouraged the concept of intensifying current prominent cropping systems through various double cropping strategies. Camelina (Camelina sativa L.) and field pennycress (Thlaspi arvense L.) are two winter oilseed crops that could potentially be integrated into the corn (Zea mays L.)–soybean [(Glycine max (L.) Merr.] cropping system, which is the prominent cropping system in the US Corn Belt. In addition to providing a feedstock for renewable aviation fuel production, integrating these crops into corn–soybean cropping systems could also potentially provide a range of ecosystem services. Some of these include soil protection from wind and water erosion, soil organic C (SOC) sequestration, water quality improvement through nitrate reduction, and a food source for pollinators. However, integration of these crops into corn–soybean cropping systems also carries possible limitations, such as potential yield reductions of the subsequent soybean crop. This review identifies and discusses some of the key benefits and constraints of integrating camelina or field pennycress into corn–soybean cropping systems and identifies generalized areas for potential adoption in the US Corn Belt.

Keywords: Camelina, cropping system intensification, double cropping, pennycress, renewable jet fuel, second-generation biofuels, winter oilseeds

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Introduction

Producing sustainable renewable fuels with little to no competition with land used for food production while simultaneously reducing society's carbon (C) footprint is an important goal of the second-generation biofuel crop industry. Land-use changes and potential subsequent greenhouse gas emission increases are main concerns associated with the production of crops for bioenergy (e.g., Fargione et al., 2008; Searchinger et al., 2008; Kim et al., 2009; Dale et al., 2011). The intensification of current cropping systems with a bioenergy crop through double or relay cropping is one strategy that may alleviate these concerns regarding land-use change (Heaton et al., 2013; Moore & Karlen, 2013). In the Corn Belt Region of the United States (Fig. 1), corn-based

cropping systems dominate the agricultural landscape, and cropland is often fallow during the winter months (Fig. 2). Because of this, winter annual oilseed crops offer potential for biofuel production while coexisting with other crops grown for food [e.g., corn, soybean, wheat (Triticum aestivum L.)]. While the inclusion of winter oilseeds into cropping systems where corn is grown continuously may also be an option, this discussion is centered on corn–soybean cropping systems because it is the dominant cropping system in the US Corn Belt, with an estimated area of 27 million hectares in the region (Table 1). In this cropping system, the oilseed crop would ideally be interseeded into corn before or immediately after corn harvest (Fig. 3) and would be harvested prior to soybean planting in a sequential double cropping system or while soybean is growing in a relay double cropping system. Benefits and limitations exist with winter oilseed crop integration into corn–soybean systems. However, the added value of winter

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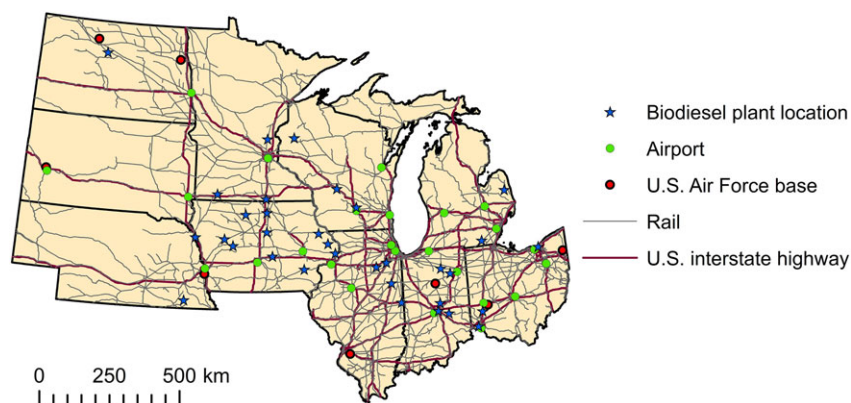
Fig. 1 Select infrastructure for biodiesel production in the US Corn Belt. Airports were those with enplanements of ≥250 000 people.
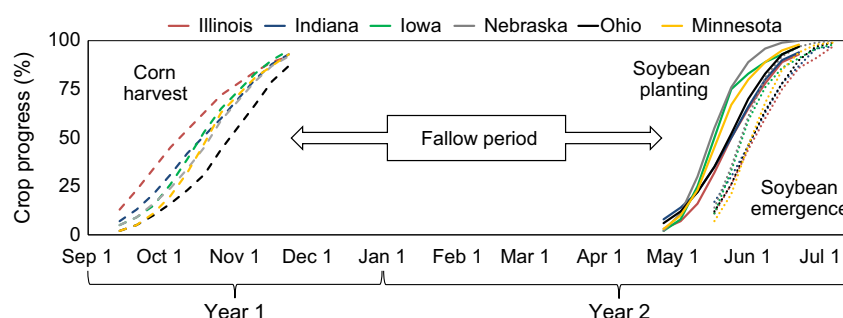

Fig. 2 Average (2009–2013) corn harvest progress (long dash line), soybean planting progress (solid line), and soybean emergence progress (short dash line) for selected states in the US Corn Belt (www.nass.usda.gov).

cropping diversity and winter cash crops may also offer relief for some of the previously reported limitations. This review identifies and discusses agronomic, environmental, and socioeconomic benefits and challenges associated with the possible implementation of this system.

Renewable fuel demands

The 2013 adjustment of the US Renewable Fuel Standard (RFS2) requires 7.3 and 10.4 billion L of biomass-based diesel and advanced biofuels, respectively, in an effort to increase domestic fuel production and decrease reliance on foreign sources (United States Environmental Protection Agency, 2013, 2015). The aviation industry also has significant interest in adopting renewable fuels that reduce carbon emissions while simultaneously being economically competitive with petroleum-based fuels. At the 2008 Aviation and Environment Summit, commitments were set to maintain current carbon emission levels by 2020 and halve emissions based on 2005 levels by 2050 (Air Transportation Action Group, 2015). In attempt to shift its reliance to sustainable fuel, the US

Federal Aviation Administration established the goal of using approximately 4 billion L yr^{-1} of renewable jet fuel by 2018 (FAA, 2011). The US Air Force and US Navy have also set renewable fuel consumption goals, where the Air Force goal is that 50% of noncontingency operations will use an alternative drop-in fuel blend by 2025 (U.S. Air Force, 2013). The Navy has set a target that 50% of total energy consumed will be from renewable sources by 2020 (U.S. Navy, 2010). Therefore, renewable fuels are planned to serve as an integral fuel source for ground- and air-based transportation in the near future and beyond. Additionally, a recent report by the US Environmental Protection Agency has concluded that emissions from aircraft endangers human health because of their contribution to global warming (United States Environmental Protection Agency, 2015), which will likely result in emission regulations imposed on the commercial aviation industry (Mouawad & Davenport, 2015).

Traditional oilseed feedstocks used for biofuel production include soybean, rapeseed/canola (*Brassica napus*), palm (*Elaeis guineensis*), and sunflower (*Helianthus annus*) (Moser, 2012). However, as noted by

Table 1 Acreage estimates for 2- and 3-year corn-soybean and alfalfa-based cropping systems in the U.S Corn Belt from 2009–13[*]

State	Corn-soybean		Corn-corn-soybean		Alfalfa-based	
	Area, ha	Distribution, %[†]	Area, ha	Distribution, %	Area, ha	Distribution, %
Illinois	4 281 810	19.8	1 153 150	21.1	31 550	1.4
Iowa	5 417 130	25.1	1 164 080	21.3	140 410	6
Indiana	2 353 080	10.9	466 910	8.5	29 450	1.3
Michigan	426 590	2	151 780	2.8	384 950	16.6
Minnesota	2 923 730	13.5	661 830	12.1	363 020	15.6
Nebraska	2 161 620	10	1 024 380	18.7	258 800	11.1
North Dakota	517 060	2.4	87 070	1.6	124 830	5.4
Ohio	1 337 550	6.2	153 190	2.8	60 650	2.6
South Dakota	1 732 970	8	311 320	5.7	220 290	9.5
Wisconsin	428 490	2	301 570	5.5	707 850	30.5
Total	21 580 030		5 475 280		2 321 800	

[*]Classification accuracy of corn, soybean, and alfalfa area by USDA-NASS Cropland Data Layers is available in a Table S1.
[†]Distribution is the proportion of a cropping system for a given state compared to the U.S. Corn Belt region.

Moser (2012), the sole use of these traditional oilseed feedstocks will likely not meet production demands mandated by the RFS2. For example, Hill *et al.* (2006) estimated that dedicating all US soybean production to biofuel would only satisfy 6% of the US diesel demand. Also, the use of prominent crops like soybean for biofuel production diminishes its opportunity to be used for food (Cassman & Liska, 2007; Tilman *et al.*, 2009; Karp & Richter, 2011), which is of increasing importance as world population is estimated to surpass nine billion by 2044 (U.S. Census Bureau, 2014). Finally, soybean production has been reported to have adverse effects on the soil environment, specifically through greater wind and water erosion susceptibility and less soil organic carbon (SOC) when compared to corn-based cropping systems (Laflen & Moldenhauer, 1979; Varvel & Wilhelm, 2008, 2011).

Alternative crops and cover crops

The aforementioned concerns have resulted in expansion of research on alternative oilseed crops for bio-based diesel and aviation fuel. Examples of second-generation oilseed crops include camelina, field pennycress, crambe (*Crambe abyssinica*), cuphea, (*Cuphea* spp.) oilseed radish (*Raphanus sativus* L.), Ethiopian mustard (*Brassica carinata*), white mustard (*Sinapis alba* L.), and flax (*Linum usitatissimum* L.), to name a few (Johnson *et al.*, 2007; Moser, 2012). These crops have several desirable characteristics including greater seed oil concentration than soybean, reported lower agricultural input requirements (Putnam *et al.*, 1993; Zubr, 1997), and potential for little or no disruption when integrated into prominent cropping systems. They can also provide environmental benefits like protection from soil erosion,

increased C inputs for potential SOC sequestration, and providing food resources and habitat for pollinators and other beneficial insects. Camelina and field pennycress are particularly viewed as attractive options for biodiesel or aviation fuel due to their desirable fatty acid profiles in addition to high oil contents (Moser *et al.*, 2009; Boateng *et al.*, 2010; Moser, 2012; Fan *et al.*, 2013). Also, significant greenhouse gas emissions reductions are expected from second-generation oilseed crops either for ground transportation or aviation fuels, especially when used in a double cropping system (Shonnard *et al.*, 2010; Krohn & Fripp, 2012; Fan *et al.*, 2013).

Double cropping strategies

Simply defined, double cropping is the agricultural practice of growing two crops on the same unit of land during the same growing season. In traditional double cropping systems, the second crop is planted following the harvest of the first. Double cropping of biomass crops has been viewed to be a potential option in northern areas of the US Corn Belt (Iowa, Minnesota, and Wisconsin), where the traditional growing season is often regarded as short (Moore & Karlen, 2013). For example, Feyereisen *et al.* (2013) concluded that winter rye (*Secale cereale* L.) could be successfully grown in a corn–soybean cropping system across the US Corn Belt, thus potentially alleviating the issue of displacing cereal crops with energy crops and avoiding significant land-use change. Additionally, land area suitable for double cropping in the US Corn Belt has increased in the last 30 years and is projected to further increase as a result of future climate change (Seifert & Lobell, 2015). A particular double cropping strategy that may help to mitigate risk, particularly in northern environments, is relay

Fig. 3 Pennycress growth following corn in a double cropping system near Ithaca, NE (top), and simultaneous camelina and soybean growth in a relay cropping system near Morris, MN (bottom).

cropping. In this type of system, the second crop (summer annual) is interplanted into the first crop (winter annual) prior to maturity, which extends the growing season for the second crop (Fig. 3). Research in the North Central USA has shown promising results with this system. For example, Gesch *et al.* (2014) reported that soybean relay-cropped with winter camelina produced greater seed and more total gross income compared to a sequential soybean–camelina double cropping system and was economically competitive with full-season monocropped soybean. Moreover, relay cropping soybean with winter camelina was shown to produce at least 50% more seed oil per hectare than growing a sole full-season soybean crop. Research similar to that performed by Gesch *et al.* (2014) will need to be conducted in other environments and on other oilseed crops to identify double cropping strategies that maximize productivity and profitability.

Potential ecosystem value

While the intensification of corn–soybean cropping systems with a winter oilseed crop would be to primarily increase opportunities for renewable diesel or hydroprocessed renewable jet fuel, its inclusion may also indirectly affect cellulosic biofuel (ethanol) from agricultural residues. Corn stover, the aboveground

biomass remaining after grain is harvested, is forecasted to be a primary feedstock for lignocellulosic biofuel production with estimated stover harvests ranging from 54 to 123 Tg yr^{-1} for the USA (Graham *et al.*, 2007; Muth *et al.*, 2013). However, harvesting corn stover, or other crop residues, without other organic amendments can have adverse effects on soil erosion susceptibility (Mann *et al.*, 2002; Jin *et al.*, 2015; Kenney *et al.*, 2015), SOC (Wilhelm *et al.*, 2004; Stetson *et al.*, 2012; Schmer *et al.*, 2014), and general soil fertility (Karlen *et al.*, 1984; Blanco-Canqui & Lal, 2009; Sindelar *et al.*, 2013). Our hypothesis is that inclusion of winter oilseed crops into corn–soybean cropping systems where corn stover is harvested may reduce, or even potentially offset in some cases, organic C losses associated with corn stover removal. For example, Blanco-Canqui *et al.* (2014) found that the inclusion of a winter rye cover crop helped offset SOC losses when stover was removed in a continuous corn system in Nebraska. Osborne *et al.* (2014) reported that a winter lentil (*Lens culinaris* Medik.)/slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Shinners] cover crop combination reduced the impact of corn stover removal on SOC in a corn–soybean cropping system in South Dakota. Research is needed to determine whether the response of oilseed cover crops would result in a deviation from this response. Corn stover removal has also been shown to increase residual nitrate-N in the soil profile following corn, particularly at N fertilizer rates that economically optimize grain yield as stover, that can often immobilize N, is absent from the soil surface (Sindelar *et al.*, 2015). Strock *et al.* (2004) found that a corn–soybean cropping system with a winter rye cover crop reduced subsurface tile water drainage discharge and flow-weighted mean nitrate concentration. Drury *et al.* (2014) reported that the inclusion of a winter wheat cover crop in a corn–soybean cropping system reduced nitrate-N loss by 14 to 16%. A recent study by Kladivko *et al.* (2014) used the Root Zone Water Quality Model to simulate residual nitrate-N dynamics in the Mississippi River Basin and concluded that residual nitrate-N loadings would be reduced by approximately 20% if cover crops were integrated into corn–soybean cropping systems. In western Minnesota, R.W. Gesch (unpublished data) recently found that winter camelina seeded in late summer as a cover crop produced as much as 1544 kg ha^{-1} (DW) of aboveground biomass containing 50 kg ha^{-1} of N by the onset of winter. Therefore, there may be opportunity to mitigate the risk of N loss if a winter oilseed crop is integrated into a corn–soybean cropping system where corn stover is removed.

Winter oilseed crops may provide other ecosystem services beyond soil and water quality improvements, including weed and pest control, and insect and wildlife

habitat (Heaton *et al.*, 2013). Johnson *et al.* (2015) reported that pennycress reduced weed biomass by >80%. Although not explicitly discussed by the authors, this response may have been related to the presence of glucosinolates, a class of secondary metabolites found in mustards (Moser, 2012), which can inhibit growth of other plants (Gimsing & Kirkegaard, 2009). This might be of practical interest in organic production systems and may also serve as a use for coproducts that remain following oil extraction. For example, Vaughn *et al.* (2005) found that defatted pennycress seed meal inhibited seedling germination and emergence of wheat and arugula [*Eruca vesicaria* (L.) Cav. Susp. *sativa* (Mill.) Thell.]. Control of pests by oilseed residue has also been reported. Mojtahedi *et al.* (1991) found that soils amended with rapeseed tissues had lower populations of root-knot nematode (*Meloidogyne* spp.).

Oilseed crops can also enhance beneficial insect populations and diversity, as several studies on the ecology of pollinators and mass-flowering crops have demonstrated. Bumble bee (*Bombus* spp.) density was found to be related positively to rapeseed availability on the landscape (Westphal *et al.*, 2003), with a higher abundance in rapeseed fields compared to wheat and Miscanthus (*Miscanthus × giganteus*) (Stanley & Stout, 2013). This effect can extend even to crops maturing later in the season; the density of bumble bees in late flowering sunflower has been shown to be enhanced by early flowering rapeseed, an effect known as temporal spillover (Riedinger *et al.*, 2014). Recently, Eberle *et al.* (2015) evaluated pollinator visitation and nectar production of camelina and pennycress grown as cover crops in Minnesota and found that visitation rates for these two oilseeds reached 67 and 22 insects min^{-1}, respectively (112 m^2-area). They also reported that, during the period of anthesis (Table 2), camelina and pennycress flowers produced 100 and 13 kg of sugar ha^{-1} in their nectar, respectively, the former of which was even greater than that of winter canola (84 kg ha^{-1}), a widely recognized pollinator-friendly plant. Both camelina and

pennycress specifically were cited by the presidentially mandated Pollinator Health Task Force (2015) as being useful early season forage resources for pollinators, which may assist in improving health of both domesticated and wild pollinators.

Solitary bee biodiversity is also enhanced by mass flowering in agricultural habitats, including increased abundance (Holzschuh *et al.*, 2013) and species richness (Diekotter *et al.*, 2014) in nearby seminatural areas, as well as increased species richness within rapeseed fields (Stanley & Stout, 2013). Pollination services rendered by bumble bees and solitary bees are increasingly important as they are recognized as more efficient pollinators in many crops and native plants compared to honey bees (*Apis* spp.), and in some cases, the only pollinator (Klein *et al.*, 2007, and sources therein). Furthermore, the declines in managed honey bee colonies as a result of a number of interacting factors (pests, disease, pesticides, stress, inadequate diet) places an increased burden on native pollinators for agricultural production and ecosystem function.

Mass-flowering crops like rapeseed are likewise attractive to pollinating syrphid flies (*Syrphidae* spp.), whose ecosystem services also include biological control resulting from predaceous larval stages that consume crop pests such as aphids (*Aphis* spp.) (Schmidt *et al.*, 2003; Haenke *et al.*, 2014). Syrphids are major visitors of pennycress and camelina, with both plants serving as a foraging resource during times when few other crops or native plants are flowering (Groeneveld & Klein, 2014). In a relay or double cropping system including a winter oilseed followed by soybean, there is potential for a temporal spillover of biological control of soybean aphid (*Aphis glycines*), analogous to the temporal spillover of bumble bees mentioned above. There is need for further study on this topic, as enhancement of natural enemies such as syrphid flies could provide a direct value by reducing pest populations and outbreaks, which in turn would reduce the economic and environmental costs of pesticide use. If oilseeds are to provide pollinator bene-

Table 2 Anthesis interval of winter oilseeds in Morris, Minnesota, and Brookings, South Dakota, 2011–2014*

| Location | Year | Camelina | | Pennycress | | Canola | |
		Begin	End	Begin	End	Begin	End
Morris, MN	2011	28 May	3 July	–	–	–	–
	2012	23 April	29 May	7 May	29 May	7 May	19 June
	2013	7 June	25 June	7 June	25 June	23 May	7 July
	2014	23 May	4 June	23 May	9 June	27 May	9 July
Brookings, SD	2013	19 June	3 July	19 June	3 July	–	–
	2014	23 May	3 June	–	–	–	–

*Ground coverage of flowers ≥1%.

fits, it will be important that they are incorporated into cropping systems in ways that enhance these benefits and do not negate them (e.g., by increasing need for insecticide applications).

Corn–Soybean cropping system demographics

A geographic analysis (2010–13) estimated that 21.6 and 5.5 million hectares are classified as 2-year (corn–soybean) and 3-year (corn–corn–soybean) cropping systems, respectively, in the US Corn Belt (Table 1). The analysis also found that crop sequences in the 2-year system were quite consistent (51 and 49%). This indicates that there are no discernable temporal acreage fluctuations as a result of crop phase changes with this cropping system. When individual states were compared, Illinois and Iowa combined, accounted for 45% of the total 2-year corn–soybean system acreage in the US Corn Belt, while Minnesota, Indiana, and Nebraska individually accounted for an additional 14, 11, and 10%, respectively. Conversely, North Dakota, Michigan, and Wisconsin (<2.5%, individually) accounted for low proportions of the 2-year cropping system acreage. Further county-level extrapolation of the acreage data displayed dense areas of 2-year corn–soybean cropping systems in central Illinois, western Iowa, and southwestern Minnesota (Fig. 4a), with a high volume of counties with 2-year corn–soybean acreage ranging from 50 000 to 150 000 hectares. Additionally, at least ten counties in Nebraska and South Dakota had acreage ranging from 50 000 to 100 000 hectares. The prevalence of 2-year corn–soybean cropping systems was <1000 hectares in western areas of North Dakota, South Dakota, and Nebraska, northern areas of Minnesota, Wisconsin, and Michigan, and southeastern Ohio. This is a function of agricultural row crop production being limited in these areas with greater production of small grains and other shorter-season and less water-intensive crops, and as a result of the prevalence of grasslands (North Dakota, South Dakota, and Nebraska) and forests (Minnesota, Wisconsin, Michigan, and Ohio) in those areas.

Total acreage of the 3-year cropping system is approximately one-fourth of that observed for the 2-year system (Table 1). However, the spatial layout of dense areas of 3-year cropping systems was generally similar to those observed for the 2-year cropping system, with some slight differences (Fig. 4b). In this case, clusters of counties with the greatest 3-year cropping system acreage (>30 000 hectares) were located in south central Nebraska and northern Illinois. The analysis also indicated that all states except Michigan and Ohio had multiple counties that had at least 10 000 hectares of the 3-year cropping system.

Adoption considerations and potential challenges

Several environmental, agronomic, and socioeconomic issues may exist as a result of intensifying a corn–soybean cropping system with a winter oilseed crop in the US Corn Belt. Additionally, these constraints may be spatially dependent. Moore & Karlen (2013) concluded that double cropping may be a feasible cropping strategy in the north central USA, pending further research. However, the system they discussed would be primarily biomass-driven, thus allowing both crops to be harvested prior to physiological maturity. The cropping system of interest in this review would require both crops (winter oilseed and soybean) to reach physiological maturity within the same calendar year, as seed/grain harvest is the primary goal of both crops. However, recent work in the north central USA has shown that double cropping winter oilseeds with soybean is attainable if agronomic management decisions (e.g., soybean cultivar selection) are modified appropriately (Gesch & Archer, 2013; Johnson *et al.*, 2015). This will be discussed in detail later.

Environmental

The inclusion of a cover crop into a cropping system is formally the concept of double cropping, where two crops are grown during the same season on the same unit of land (Gesch & Archer, 2013; Moore & Karlen, 2013). The concept of a double cropping system is to better utilize the resources available during the active growing season, particularly growing degree unit (GDU) availability. Both Helsel & Wedin (1981) and Moore & Karlen (2013) concluded that areas in the north central region, where the growing season is often regarded as short when compared with other areas of the USA, can support double cropping systems if at least one, if not both, of the crops is harvested for forage. The biomass harvest of the first crop would theoretically result in the planting of the second crop at a date that would not significantly deviate from a traditional planting date, barring unfavorable weather conditions (e.g., wet soils) that interfere with timely planting. Winter oilseed growth could help reduce the potential for planting delays in wet conditions by utilizing water during late fall and early spring periods and by improving soil structure to increase internal drainage and support field equipment.

In double cropping systems where the first crop is harvested for seed, planting of the second crop may often occur after the 'traditional' planting window (Fig. 2). For example, Johnson *et al.* (2015) planted soybean following pennycress maturation in early- to mid-June in a 2-year study in Minnesota, while Gesch &
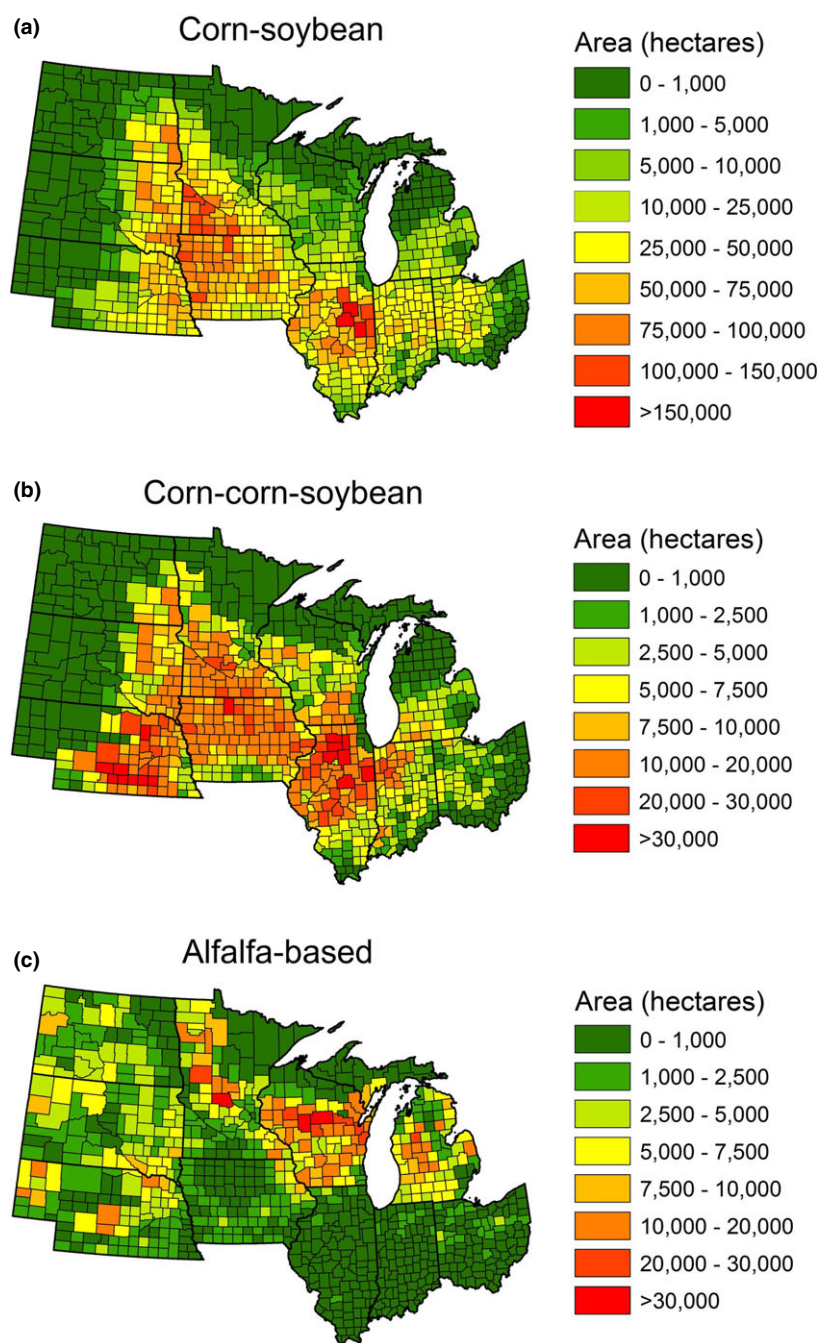
Fig. 4 Acreage estimates (2010–2013) by county in the US Corn Belt for (a) 2-year corn–soybean, (b) 3-year corn–soybean, and (c) alfalfa-based cropping systems.

Archer (2013) planted soybeans following camelina in late June to early July in a 2-year study in Minnesota. These dates were at least 2 to 3 weeks later than recommended for optimum soybean production in that state. In a research trial in Nebraska, soybeans were planted after pennycress harvest in early- to mid-June (M.R. Schmer & A.J. Sindelar, unpublished data). As GDU availability will often be one of the primary limiting factors to grain production in double cropping systems, particularly in the north central USA, its availability was estimated for the second crop based on 30-year normal temperature data from 15 June to the average first frost (≤0 °C) date (Fig. 5a). This analysis found that GDU availability over this time period ranged from 956 to 3070 GDU across the US Corn Belt region and 1396 to 3070 in counties with at least 1000 hectares of 2-year

corn–soybean cropping systems. The limited amount of GDUs over this time period in Wisconsin, Minnesota, and North Dakota may result in either a forage crop or soybean being the preferred second crop in a double cropping system. The selection of indeterminate soybean cultivars (those that continue vegetative growth during reproductive development) may be better suited for compressed growing seasons than other major crops with a determinate growth process (e.g., corn, grain sorghum). Foley *et al.* (1986) evaluated yield performance of determinate and indeterminate soybean lines in Minnesota and found that yields of indeterminate lines were often greater. While quantification of GDU requirements of soybean is difficult, Kandel & Akyüz (2012) estimated that maturity group (MG) 00 soybean required at least 1679 GDU to reach physiological maturity. Another report by Kandel & Akyüz (2011) estimated that the GDU requirement of a MG 0 soybean ranged from 1542 to 1837 GDU. While the lower requirement of these ranges should not be considered to be the absolute minimum GDU requirement, it does at least suggest that there is some degree of risk that soybean growing in a double cropping system may not often reach physiological maturity in far northern areas of the US Corn Belt. However, the risk of the growing season ending prior to the secondary crop reaching physiological maturity should decrease if a proper soybean cultivar is selected to account for the condensed growing season. This issue may become less problematic if relay cropping strategy is implemented. Gesch *et al.* (2014) demonstrated that soybean could be produced successfully by interplanting it into winter camelina in the spring at a normal or near-normal time for western Minnesota. Furthermore, this technique allowed the use of a standard Maturity Group soybean for the region (MG I), whereas sequential double cropping required the use of a shorter-maturity soybean variety (MG 00).

Water availability through precipitation is the other primary environmental variable that may influence the success of a double cropping system. However, the overall influence of cover crops on subsequent crop yields is conflicted. For example, Olson *et al.* (2014) found no negative effects of hairy vetch (*Vicia villosa* Roth) and rye cover crops on corn and soybean production, respectively, in Illinois. In Nebraska, a winter rye cover crop reduced subsequent corn grain yield in one of 3 years, but had no effect in the other two (Kessavalou & Walters, 1997). Acuña & Villamil (2014) evaluated the effects of several cover crop species and mixtures on subsequent soybean production in Illinois and found that there was no yield reduction when compared with the conventional treatment. In South Dakota, seeding a cover crop mixture following wheat did not
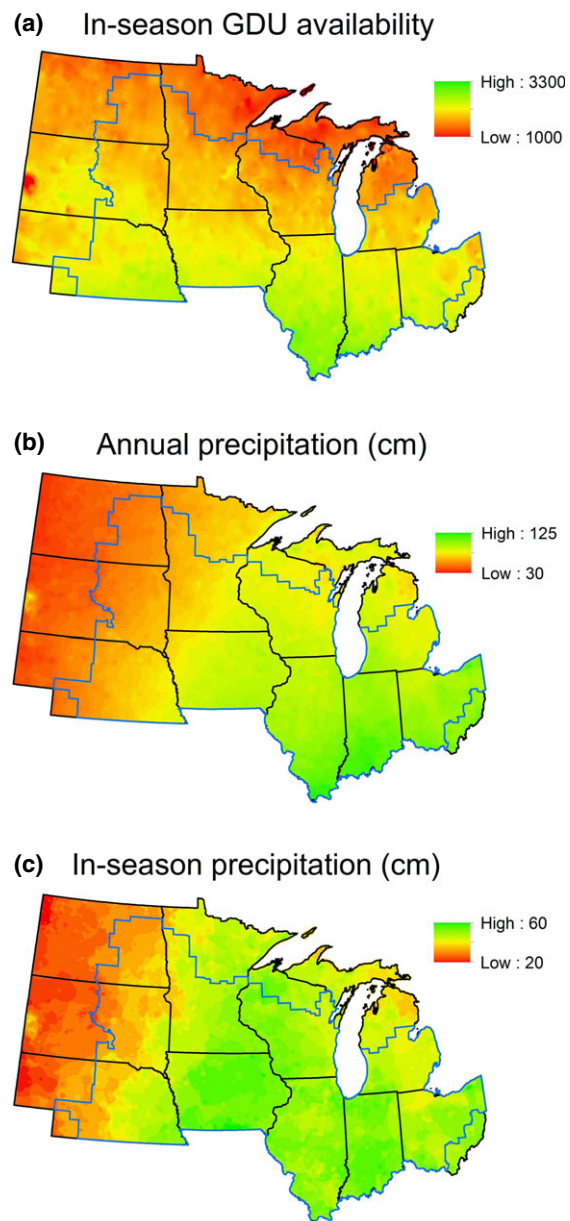

Fig. 5 Long-term (30 year) (a) in-season growing degree unit (GDU) availability, (b) annual precipitation, and (c) in-season precipitation in the US Corn Belt. Area within the blue outline identifies the generalized geography of ≥1000 hectares county^{-1} of 2-year corn–soybean cropping systems.

affect corn grain yield the following year in a low or high water stress environment, but did reduce yield at a site with moderate water stress (Reese *et al.*, 2014). At this site, cumulative soil water in the 30- to 60-cm depth was reduced in treatments with the cover crop mixture by 15%. However, no soil water changes occurred in the low- or high-stress environments with the use of the cover crop mixture. Lastly, winter rye cover crops in Minnesota reduced soybean yield by one-third in

1 year, but had no influence in another for both short- and full-season cultivars (Forcella, 2013). With regard to winter oilseeds, in a camelina–soybean double cropping study, Gesch & Johnson (2015) found that water use for sequentially and relay-cropped soybean in Minnesota was greater than continuous soybean, but absolute differences were not large. These authors concluded that these double cropping systems can be used feasibly in most rain-fed agricultural areas in the US Corn Belt region.

The region of interest in this review exhibits a considerable range in average annual precipitation, with as little as 33 cm received in western Nebraska to 124 cm in Illinois (or 41 to 124 cm within the region that supports 1000 ha county^{-1} corn–soybean cropping system) (Fig. 5b). When in-season precipitation was calculated according to the same parameters explained for GDU availability, a spatial precipitation gradient from west to east that was similar to annual precipitation was observed (Fig. 5c). Over the hypothetical growing season for soybean, in-season precipitation ranged from 20 to 60 cm across the region (24 to 60 cm within 1000-hectare county^{-1} corn–soybean geography). While in-season and annual precipitation can serve as an initial gauge, the overall suitability will ultimately be determined by water demand by the combined needs of crop (T) and evaporative demand (E), which is defined as evapotranspiration (ET). As water demand can fluctuate on both macro- (Robinson & Nielsen, 2015) and micro-scales (Sadler et al., 2002), to explicitly identify or rule out suitable areas at this point would be difficult, if not inappropriate. However, as evaporative demand generally decreases as the distance from the southern US Plains increases, a logical hypothesis is that the core area of the US Corn Belt would be under less restriction. Furthermore, we speculate that locations restricted by water availability will primarily be located in central and western areas of Nebraska, South Dakota, and North Dakota. However, even exclusion of areas in these states is not necessarily certain nor appropriate at this point because of the confounding influence of supplemental irrigation. According to the USDA-National Agricultural Statistics Service (2008), approximately 3.5 million hectares of agricultural land is irrigated in Nebraska, accounting for 15% of total irrigated land in the USA In comparison, 1.25 million hectares are irrigated in the remaining nine states in the USA Corn Belt, combined. Therefore, opportunities for cropping system intensification with winter oilseed cover crops will likely exist in many areas in the western Corn Belt, particularly in Nebraska, as a result of supplemental irrigation. In these areas, the potential increase in water demand would need to be weighed against any limitations in irrigation water supply. Further identification of

irrigated land in these regions would be necessary to identify acreage where cropping system intensification would not be practical.

Finally, landscape attributes, specifically slope, could also affect land availability for a corn–soybean cropping system with stover removal and winter oilseed crop inclusion. In several areas in the US Corn Belt, scenarios exist where at least 1000 hectares of corn–soybean cropping systems reside in areas with landscape slopes of 6% or greater (Fig. 6). A point of emphasis by many has been that corn stover removal rates need to be at levels that simultaneously maintain SOC and control wind and water erosion, and that areas exist where corn stover removal may not be appropriate (e.g., Mann et al., 2002; Nelson, 2002; Wilhelm et al., 2007; Johnson et al., 2010). As water erosion is affected by landscape slope, this becomes a critical attribute for determining landscape suitability for such a cropping system. Graham et al. (2007) reported that the area appropriate for corn stover removal decreases significantly as erosion susceptibility increases.

Coincidentally, however, there may be situations where the addition of a winter oilseed crop may allow for stover removal when previously declared unacceptable as a result of landscape erosion constraints. In a 2-year study at a sloped site in Iowa, Kaspar et al. (2001) found that a winter rye cover crop interseeded with soybean reduced interrill erosion and runoff in both years, while an oat (Avena sativa L.) cover crop reduced erosion and runoff in 1 year. Bonner et al. (2014) used an integrated modeling framework to evaluate the effect of cover crops on corn stover supplies and found that their inclusion would increase sustainable stover removal rates across a range of slope gradients, although it became less impactful at slopes >4%. Therefore, based on initial results from this study, it seems that the amount of harvestable stover in this scenario may still be rather small.

Agronomic

From a production standpoint, soybean yield reduction associated with delaying the planting of the crop in a double cropping system is probable, regardless of geographic location. The review of 17 studies where soybean planting was delayed revealed a clear yield response when planting was delayed by at least 19 days, although the magnitude varied among sites (Table 3). In this review, all but four site-years exhibited a yield loss of 4 to 28% when planting was delayed. Two cases existed where no yield losses occurred with delayed planting in Minnesota and Wisconsin, although planting was delayed into late May by 19 and 20 days, respectively (Leuschen et al., 1992; Pedersen & Lauer,
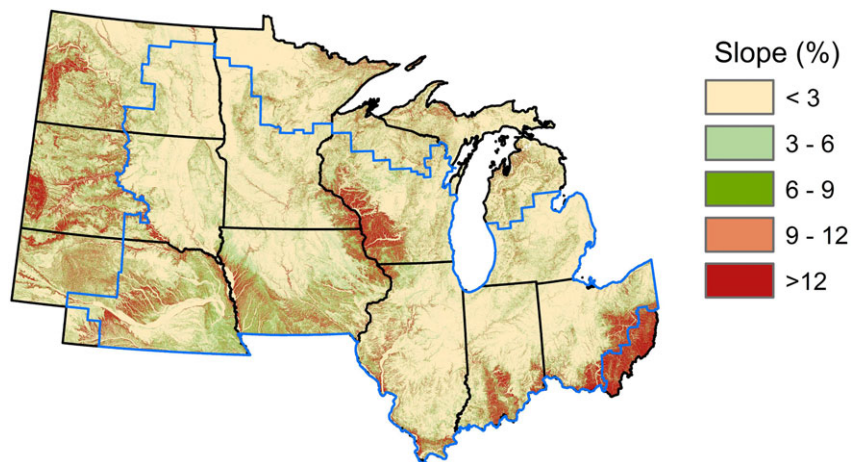
Fig. 6 Landscape slope in the US Corn Belt. Area within the blue outline identifies the generalized geography of ≥1000 hectares of 2-year corn–soybean cropping systems.

2003). Two studies used in this review evaluated soybean production in double cropping systems (LeMahieu & Brinkman, 1990; Gesch & Archer, 2013). In Wisconsin, LeMahieu & Brinkman (1990) reported that planting in late June (delay of 41 days) as a result of growing a winter rye crop for biomass reduced subsequent soybean yield by 26%. In comparison, delaying soybean planting over the same period without a double crop reduced soybean yield by 27%. In Minnesota, Gesch & Archer (2013) reported that soybean yield decreased by 20% when it was planted following camelina harvest when compared with continuous soybean sown in early May (52-day difference between planting dates). Based on these results, producers must be aware of and amendable to probable soybean yield reductions associated with grain-based double cropping systems, regardless of location in the US Corn Belt. However, it is important to consider is that the reduction in soybean yield may not necessarily equate to less net profit for the cropping system when the economic value of the oilseed crop is considered.

Several authors (e.g., Carter & Boerma, 1979; Wilcox & Frankenberger, 1987; Specht *et al.*, 2012) have stated that reductions in soybean yield as a function of delayed planting is a result of the reduction of main stem nodes. Specht *et al.* (2012) also noted that a new node is produced on the main stem every 3.7 days, regardless of planting date. Therefore, soybean plants planted after 'traditional' planting dates have less opportunity for nodal development. An observed reduction in main stem node number reported by Carter & Boerma (1979) also coincided with a reduction in plant height by 14 to 39% when planting was delayed. Because of this physiological response and the aforementioned planting date studies, there are likely limited scenarios where delaying soybean planting to mid- to

late June would not result in some degree of yield reduction. However, additional research is clearly needed to identify crop management practices that reduce this yield gap as a result of delayed planting in double cropping systems.

An agronomic-associated landscape constraint for winter oilseed adoption may be temporal and spatial proximity to alfalfa (*Medicago sativa* L.)-based cropping systems. Cropping systems where alfalfa precedes at least 1 year of corn can be quite attractive as a result of the legume N credit supplied to the subsequent corn crop (Fox & Piekielek, 1988; Bundy & Andraski, 1993), and scenarios can exist where second-year corn following alfalfa does not require additional N fertilizer (Yost *et al.*, 2014). Alfalfa with high protein concentration is of particular value to the dairy industry, as it has been shown to increase milk production (Wu & Satter, 2000; Olmos Colmenero & Broderick, 2006), among other reasons. Therefore, areas or states with a prominent dairy industry and subsequent large areas of alfalfa production (Table 1, Fig. 4c) will require thoughtful planning and placement of cropping systems utilizing some types of winter oilseed crops (e.g., pennycress and camelina). This is because their temporal or spatial 'escape' into an alfalfa-based cropping system may negatively influence quality and/or palatability. Although most research on the reduction of alfalfa forage quality is dedicated to other common weeds, a general conclusion is that polycultures of alfalfa and nontarget plant species often produce less dry matter, have lower forage quality, and are less palatable than monoculture alfalfa (Temme *et al.*, 1979; Marten *et al.*, 1987; Fisher *et al.*, 1988). Moyer & Hironaka (1993) reported that the proportion of digestible crude protein by sheep and subsequent digestible energy of pennycress was lower than that with alfalfa, despite crude protein concentration being similar

Table 3 Reported responses of soybean grain yield to delayed planting across the US Corn Belt

State	Site(s)	Study length, years	Average planting date		Yield change $(D_1–D_2)$, kg ha^{-1}	Reference
			Date 1 (D_1)	Date 2 (D_2)		
Illinois	Urbana	3	13 May	18 June	−458 (13%)	Beaver & Johnson (1981)
	Brownston	2	20 May	14 June	+478 (28%)	Beaver & Johnson (1981)
Illinois	Urbana	2	12 May	14 June	−715 (22%)	Anderson & Vasilas (1985)
Indiana	West Lafayette	3	12 May	22 June	−531 (21%)	Wilcox & Frankenberger (1987)
Indiana	West Lafayette	2	10 May	10 June	−620 (15%)	Robinson et al. (2009)
Iowa	Ames	3	14 May	8 June	−205 (8%)	Krell et al. (2005)
Iowa	Newton	3	11 May	7 June	−200 (7%)	Perez-Bidegain et al. (2007)
Iowa	Ames, Crawfordsville, De Witt, Nashua, Nevada, Whiting	4	29 April	8 June	−1055 (25%)	De Bruin & Pedersen (2008)
Minnesota	Morris	4	3 May	22 May	−215 (7%)‡	Leuschen et al. (1992)
	Lamberton	3	4 May	25 May	+38 (2%)	Leuschen et al. (1992)
	Waseca	4	8 May	28 May	−303 (10%)	Leuschen et al. (1992)
Minnesota	Waseca, Lamberton, Madison, Rosemount	3	15 May	14 June	−590 (23%)	Coulter et al. (2011)
Minnesota*	Morris	2	8 May	29 June	−463 (20%)	Gesch & Archer (2013)
Nebraska	Clay Center	3	7 May	15 June	−390 (13%)	Elmore (1990)
North Dakota	Fargo, Casselton	2	21 May	17 June	−820 (26%)	Helms et al. (1990)
Ohio	Hoytville, South Charlston	3	1 May	10 June	−834 (25%)	Beuerlein, (2013)
Wisconsin†	Arlington	2	12 May	22 June	−1004 (27%)	LeMahieu & Brinkman (1990)
		2	12 May	22 June	−941 (26%)	LeMahieu & Brinkman (1990)
Wisconsin	Arlington	4	15 May	13 June	−572 (17%)	Oplinger & Philbrook (1992)
Wisconsin	Hancock	2	1 May	30 May	−565 (21%)	Grau et al. (1994)
Wisconsin	Arlington	4	5 May	25 May	−170 (4%)	Pedersen & Lauer (2003)
	Hancock	4	10 May	30 May	−600 (14%)*	Pedersen & Lauer (2003)

*Soybeans were double cropped, with camelina being the preceding crop.
†Soybeans were double cropped, with barley being the preceding crop.
‡Authors reported no statistical change.

between the two plant species. Pennycress can also have adverse effects on livestock and their corresponding milk and meat products if excess quantities are consumed due to high erucic acid levels in its seed oil and glucosinolates, specifically sinigrin, in its seed and vegetative tissues (Best & MCIntyre, 1975; Warwick et al., 2002; Sedbrook et al., 2014). For example, consumption of large quantities of plants containing glucosinolates by dairy cattle can result in off-flavored milk products (Fenwick et al., 1982). Also, beef cattle carcasses have been shown to have slight to strong odor when fed high proportions of pennycress seed immediately before processing, yet no discernable odor existed when the time period between feeding and processing was 24 h or greater (Whiting et al., 1958) Despite this effect on animals and corresponding products, myrosinase, the enzyme responsible for the degradation of sinigrin into the toxic compounds isothiocynate and allyl isothiocynate, can be successfully deactivated through a heat treatment prior to seed crushing (Sedbrook et al., 2014). Furthermore, Hojilla-Evangelista et al. (2014) reported

that two protein recovery methods, saline extraction and acid precipitation, performed on defatted pennycress seed also can effectively recover protein extracts that are sinigrin-free. This finding is significant, as protein content in pennycress seed meal can range from 20 to 27% (Hojilla-Evangelista et al., 2013; Selling et al., 2013), and thus could be a serviceable livestock feed. Conversely, camelina should be less problematic than pennycress in this regard. Research has shown that camelina seed meal is low in glucosinolates (Schuster & Friedt, 1998), can serve as a potential livestock feed (Korsrud et al., 1978; Moriel et al., 2011; Szumacher-Strabel et al., 2011; Colombini et al., 2013), and is approved by the US Food and Drug Administration for use in cattle and chicken feeds (up to 10% of total ration). Long-term management plans in addition to short-term strategies should also be considered in areas with dense dairy production or fields that may be seeded to alfalfa in the near future. However, a counterpoint to this issue is the recent availability of glyphosate-tolerant alfalfa cultivars that can aid in control of nontarget plants. Therefore,

any issues regarding winter oilseed production in or near alfalfa-based cropping systems may be alleviated if widespread adoption of glyphosate-tolerant alfalfa cultivars occurs.

Both pennycress and camelina are considered minor weeds to select crops. For pennycress, most yield losses associated with its presence have been reported with canola, wheat, and safflower (*Carthamus tinctorius* L.) in Canada (Warwick *et al.*, 2002). Camelina is a minor weed in flax (Putnam *et al.*, 1993), resulting in its alternate name as *false flax*. Despite both crops being historically regarded as a weed and a recent risk assessment by the USDA-Animal and Plant Health Inspection Service (APHIS) classifying pennycress as a high risk potential for spread and impact (USDA-APHIS, 2015), we hypothesize their impact as a volunteer weed on corn and soybean production to be low. This is because chemical control of both plants is historically quite successful. Francis & Warwick (2009) concluded that agronomic impact of camelina in corn–soybean cropping systems should not be an issue when proper herbicide chemistries are used. Pennycress is also quite susceptible to multiple herbicide chemistries (Warwick *et al.*, 2002), including glyphosate and glufosinate (Sedbrook *et al.*, 2014). Therefore, a pre-emergence herbicide application at corn or soybean planting should provide adequate control of most pennycress or camelina seeds as they germinate, and any escapes can be managed with postemergence chemistries. Additionally, the majority of soybean currently grown in the US Corn Belt has resistance to glyphosate. In other situations, herbicide chemistries such as 2,4-dichlorophenoxyacetic acid, imazethapyr, and acifluorfen should also successfully control escapes.

From a field management standpoint, a critical practice associated with oilseed and cover crop productivity is proper stand establishment. Studies that have evaluated a winter oilseed–soybean double cropping system have typically followed wheat (Phippen & Phippen, 2012; Gesch & Archer, 2013). Depending on type, wheat harvest occurred no later than mid-August, thus allowing adequate time for fall growth of the winter oilseed when direct-seeded into the soil. Gesch & Cermak (2011) demonstrated that although stand establishment of winter camelina can differ by year and tillage system (e.g., conventional vs. no-till) in the northern US Corn Belt, they found that final plant population density varied little by planting date when seeded from early September to mid-October. However, the greatest seed yields and oil content were generally obtained for plants seeded in late September to early October. Similar results have been obtained for pennycress (R.W. Gesch, unpublished data). Winter camelina has also been successfully established in North Dakota in September and even as a dormant seeding in late October (D.W. Archer, unpublished data). Moreover, Gesch *et al.* (2014) have shown that winter camelina seeded in mid- to late October in west central Minnesota, just weeks before permanent soil freezing occurred, exhibited adequate winter survival and spring growth. This indicates that, in some of the southern regions of the US Corn Belt (e.g., Iowa, Illinois, and Nebraska), it may be possible to successfully establish winter camelina and pennycress following harvest of corn for grain. Nevertheless, this type of management schedule may not be applicable to many corn–soybean cropping systems unless (1) the entire corn plant is harvested for silage prior to reaching physiological maturity or (2) an early maturing hybrid is used. Typically, corn hybrids are selected based on maturities that best exploit the growing season when grain yield optimization is the primary goal. This practice, in turn, results in little growing season remaining after the corn plants reach physiological maturity, grain is allowed to dry to an appropriate moisture content, and harvest occurs (Fig. 2). Therefore, aerial seeding of the winter oilseed crop may be necessary in most areas, particularly for crops/cultivars that require vernalization. Baker & Griffis (2009) concluded that aerial seeding of winter rye in northern areas of the US Corn Belt may help mitigate growth limitations imposed by a short growing season. A survey by Singer (2008) found that 8% of cover crops were aerially seeded in a portion of the Corn Belt (Illinois, Indiana, Iowa, and Minnesota), compared to 68 and 21% for direct drilling and broadcast spreading, respectively. However, 62% of cover crops in this area were not harvested. Although not explicitly discussed by Singer (2008), we speculate that the proportion of cover crops aerially seeded in this area is a function of cost, and that seed from few, if any, of these cover crops would have been harvested. Additionally, we hypothesize this proportion would increase if cash-positive winter crops were used or if incentives for cover crops are provided.

Benefits do exist for aerially seeding winter cover crops when compared with other traditional methods. These include offering a greater temporal window for seeding, elimination of machinery traffic, which may help to reduce soil compaction, and less time requirement as aerial seeding can often be performed in a shorter amount of time than other traditional methods (Wilson *et al.*, 2013). To some, however, the disadvantages outweigh the benefits. These include a short-time period for fall growth, cost of aerial application, seed predation, and proper stand establishment (Wilson *et al.*, 2014). Barnett & Comeau (1980) evaluated aerial seeding effects on the germination of wheat, oat, and barley (*Hordeum vulgare* L.) and found that the number of plants germinated was substantially less than direct-

seeded or broadcast treatments. Therefore, to compensate for poor germination of aerially seeded crops, seeding rates may need to be increased, which would subsequently increase input costs. However, both camelina and pennycress have very small seeds compared to, for example, winter rye (about 0.8, 0.8, and 33 g 1000^{-1} seeds, respectively), which would serve to lower aerial seeding costs on a unit-area basis (Robinson, 1987; Phippen et al., 2010; Miedaner et al., 2014).

Other considerations include information and techniques needed in managing these crops, and the need for continued breeding efforts to improve characteristics of these crops. For example, risk of seed loss due to shatter can be a serious concern for camelina and pennycress, with complete yield loss potentially occurring in a single untimely rain and wind event (D.W. Archer, unpublished data). Fortunately, genetic similarities of camelina and pennycress with Arabidopsis have resulted in expedited progress toward the genomic understanding of both crops (Gehringer et al., 2006; Dorn et al., 2013, 2015; Nguyen et al., 2013). For pennycress, this can potentially accelerate its domestication through improvement of several traits including seed oil quality and quantity improvement, reduction of glucosinolates, seed dormancy manipulation, flowering and senescence synchronization, and pod shatter reduction (Sedbrook et al., 2014). Also, availability of herbicides labeled for use in these crops is limited, presenting a challenge for in-season weed management, particularly in no-till production systems. One possible solution to this issue is herbicide-resistant cultivars, such as camelina with resistance to acetolactate synthase inhibitor herbicides (Walsh et al., 2012). While initial research has demonstrated that management practices can be adjusted to overcome some of these constraints (e.g., Gesch et al., 2014), additional crop development and agronomic management research is clearly needed.

Socioeconomic

Despite most cover crop research generally occurring in the past quarter century, its benefits have long been recognized (e.g., Odland & Knoblauch, 1938; Beale et al., 1955; Moschler et al., 1967; Mitchell & Teel, 1977). Some of these include erosion control (Kaspar et al., 2001), soil organic matter additions (Ding et al., 2006), nitrate-N leaching reductions (Kladivko et al., 2014), and weed suppression (Teasdale, 1996). Furthermore, the addition of a cover crop into a corn-based cropping system with stover removal may help to offset some of the adverse effects on soil properties (Fronning et al., 2008; Blanco-Canqui et al., 2014) and may even increase profitability of these cropping systems (Pratt et al., 2014). However, despite these advantages, adoption by

farmers is low to date. A survey by Singer et al. (2007) found that 18% of farmers in Illinois, Indiana, Iowa, and Minnesota had used a cover crop, and only 6% of the land area for the average-sized farm was seeded to cover crops in 2005. When farmers do indeed integrate cover crops into their cropping systems, it is because of the benefits associated with cropping system diversification, erosion control, organic matter addition, weed suppression, and N addition by leguminous cover crops (Mallory et al., 1998; Stivers-Young and Tucker, 1999; Snapp et al., 2005; Singer et al., 2007). However, as at least partially reflected in low adoption rates, many farmers feel the disadvantages outweigh the benefits. A farmer survey by Mallory et al. (1998) identified cost, potential influence on the subsequent crop, and weed problems as main concerns. Surveys by Stivers-Young & Tucker (1999) and Snapp et al. (2005) also identified cost as a concern. Despite the cash crop potential of winter oilseed crops, the limited market for their seed still makes these cover crops a cost concern. Additionally, prospective winter oilseed crops like pennycress and camelina are regarded as weeds in some cropping systems. This may further dissuade farmers from adopting these crops, particularly as pennycress seed requires a maturation period, which can increase its persistence in the seedbank (Warwick et al., 2002). However, use of nondormant pennycress cultivars (Isbell et al., 2015) may decrease this persistence, and both camelina and pennycress are easily controlled by commercially available herbicides.

From a direct-cost standpoint, cropping systems integrating winter cover or oilseed crops may be less profitable, especially if they have adverse effects on subsequent crops. Bollero & Bullock (1994) estimated a net loss of $11 hectare^{-1} when a hairy vetch cover crop preceded corn and grain sorghum [Sorghum bicolor (L.) Moench] in Illinois. Mallory et al. (1998) reported that when only the sole N value of a legume cover crop was considered, it was not economically advantageous when compared with fertilizer N. However, recent research has shown that corn-based cropping systems with stover removal maintain or increase profitability when an annual ryegrass (Lolium multiflorum Lam.) or crimson clover (Trifolium incarnatum L.) cover crop is added to the cropping system (Pratt et al., 2014). Gesch et al. (2014) reported lower net return for a sequential double crop camelina–soybean system when compared with monoculture soybean. However, in that same study, they also reported similar net returns between monoculture soybean and a relay-cropped camelina–soybean system when the camelina was treated with glyphosate seven to 10 days before harvest. Therefore, market values of winter oilseeds likely will need to be established before an increase in adoption of winter oilseed crops

occurs. These initial findings are promising and certainly warrant further research on the topic, particularly with winter oilseed crops that may further provide monetary value.

Conclusion

Inclusion of winter oilseed crops into corn–soybean cropping systems in the US Corn Belt may simultaneously provide a cash-positive commodity crop used for renewable diesel or hydroprocessed aviation fuel in addition to the wide range of ecosystem services often observed with cover crops. The geographic analysis conducted for this discussion identified 21.5 and 5.6 million hectares that are grown in corn–soybean and corn–corn–soybean cropping systems in the US Corn Belt, with the densest areas generally located in Illinois, Iowa, and southern Minnesota. However, what remains unknown is the proportion of these cropping systems that ultimately would be used as adoption of biomass cover crops in the US Corn Belt is low to date. A survey by Singer *et al.* (2007) reported 56% of farmers would adopt cover crops if financial cost sharing for the cover crop was available. Consequently, the additional value of the seed from a winter oilseed crop quite possibly may incentivize farmers to adopt these crops.

Environmental, agronomic, and socioeconomic obstacles resulting from integrating winter oilseed crops into Midwestern corn–soybean cropping systems do exist, and further research is needed in all of these areas in an attempt to reduce or minimize them. Initial research has already demonstrated that management practices can be adjusted to overcome some of these constraints (e.g., Gesch *et al.*, 2014). Management practices for a winter oilseed crop plausibly may vary slightly among areas within the US Corn Belt, much like management practices for corn and soybean can often vary slightly across the region. Regardless of these constraints, a corn–soybean cropping system where corn stover is removed and a winter oilseed crop is grown theoretically offers great potential to produce multiple independent sources for food, fuel, and fiber. However, more research is needed regarding the environmental and economic viability and sustainability of this intensified cropping system over a larger geographical area throughout the Corn Belt region and other areas in the USA.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. User accuracy of corn, soybean, and alfalfa classification by USDA-NASS Cropland Data Layers, 2010–13.